Subseasonal and Seasonal Prediction in the GMAO, with an Emphasis on the Impacts of Soil Moisture

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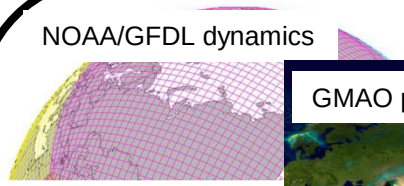
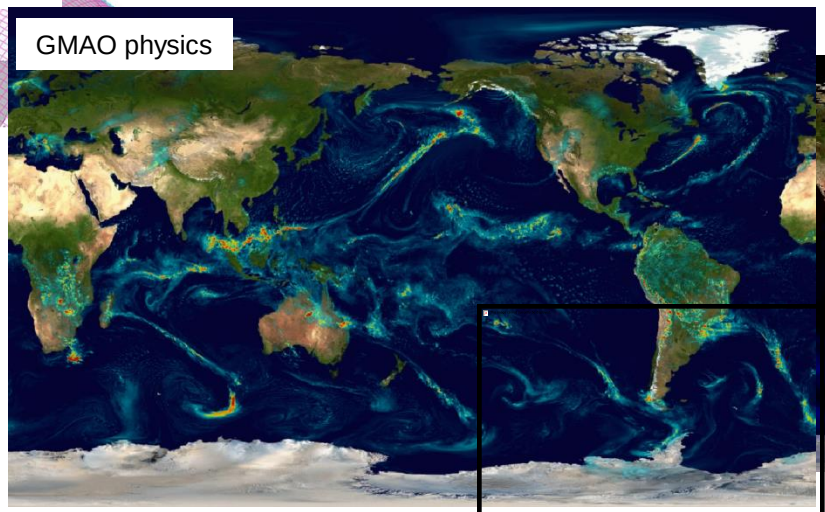
(with slides provided by many others)

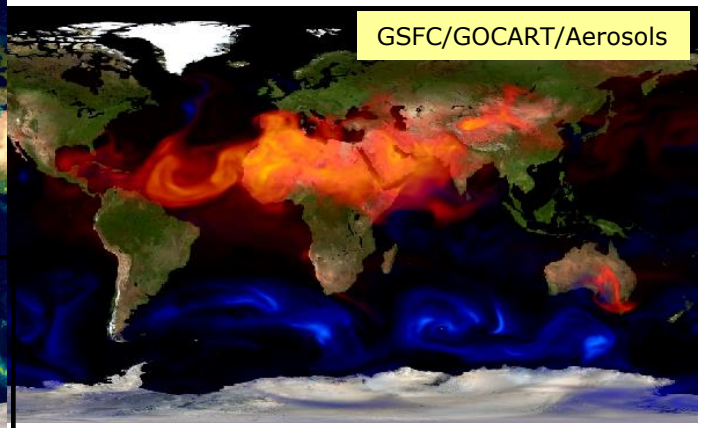
Topics covered:

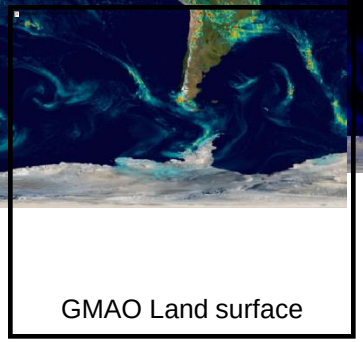
- Overall design of the GMAO seasonal forecast system
- How well does it do? (A focus on drought and hot summers)
- GMAO studies of how soil moisture information contributes to prediction skill
- Expectations for improved soil moisture estimation through the use of new sensors

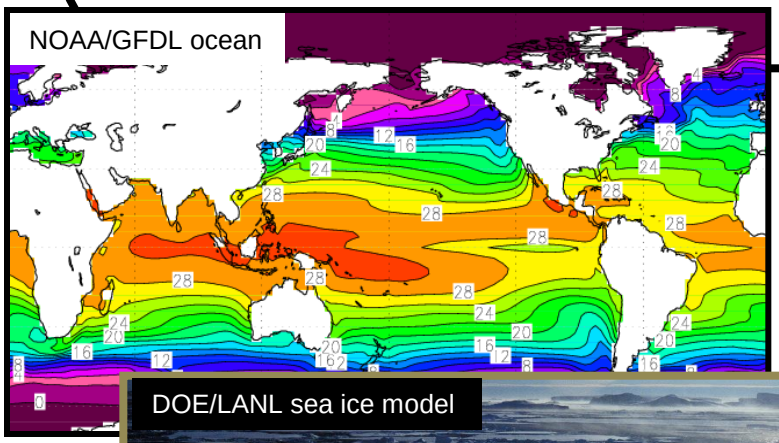
GEOS-5 AOGCM for seasonal forecasts

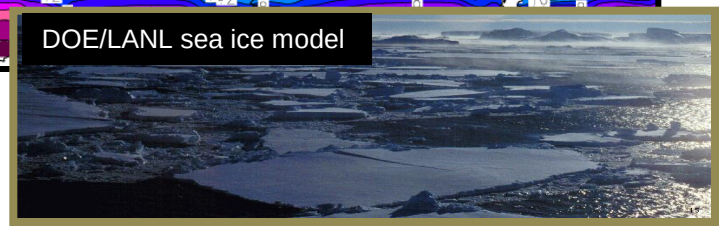












The GEOS-5 AOGCM for S-I Climate

GEOS-5 AGCM	➢ 1º lat. X 1.25º lon. X 72L ➢ surface to 0.01hPa ➢ Fortuna-2_5
OGCM: MOM4	➢ MOM4p1 ➢ 1/2º lat. x 1/2º lon. with 1/4º equatorial refinement ➢ 40 vertical levels ➢ Tripolar grid ➢ z coord; conservative temp., KPP+tidal mixing
CICE v4.1	➢ Sea-ice thermodynamics ➢ Sea-ice dynamics and advection ➢ Ridging parameterization
	➢ 1981-present, 11+ ensemble members per month, 9-month forecasts

Air-sea coupling interval: 30 minutes

GMAO Catchment Land Model

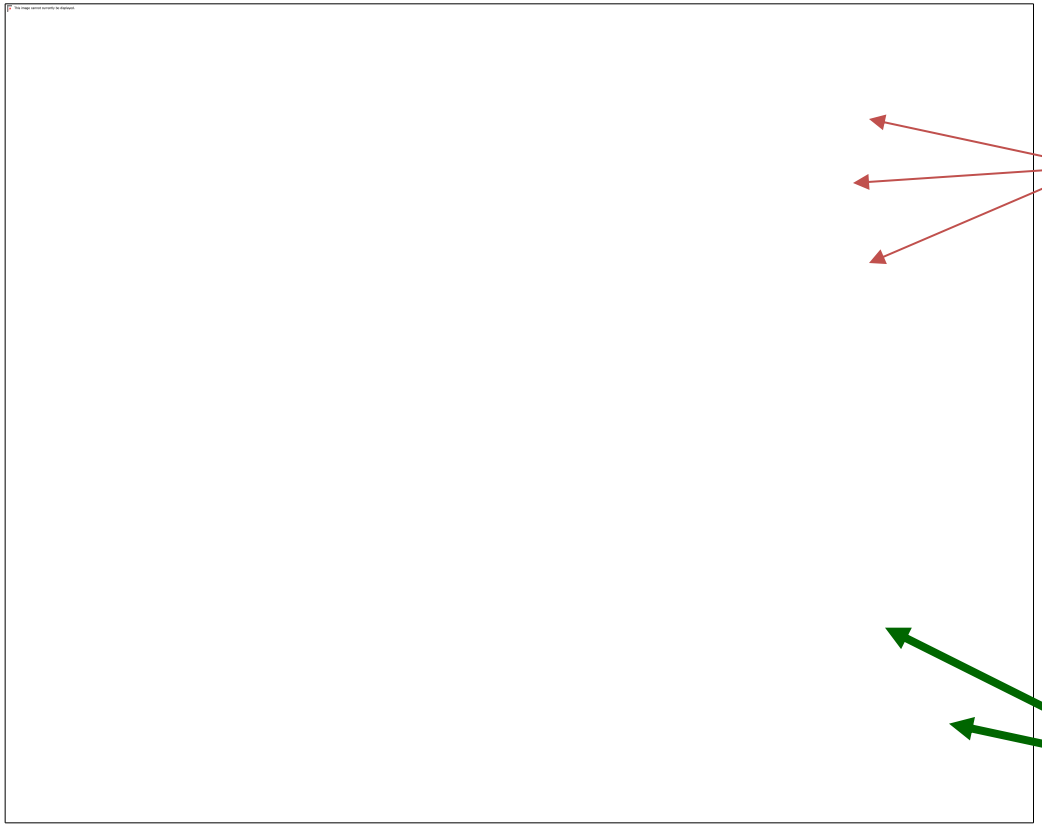
- Conservative energy and water balance calculations over each modeled land element
- Vegetation calculations (transpiration, interception, …) follow that of earlier GSFC Mosaic model (Koster and Suarez, 1996).
- Snow modeled with N layers, keeping track of heat, water, density, and areal fraction variations (Stieglitz et al., 2001).
- Subsurface ground thermodynamics treated with 7-layer model.
- Albedos constrained to realistic MODIS-based values.
- Vegetation parameters (type, LAI, greenness) derived from satellite-based datasets.
- *And, most importantly, the spatial heterogeneity of soil moisture within the land element is treated explicitly…*

The GMAO Catchment land model explicitly captures soil moisture's spatial heterogeneity:

-- *How it varies with topography*

-- *How it varies dynamically in time*

-- *How these variations affect evaporation, surface runoff, and baseflow*



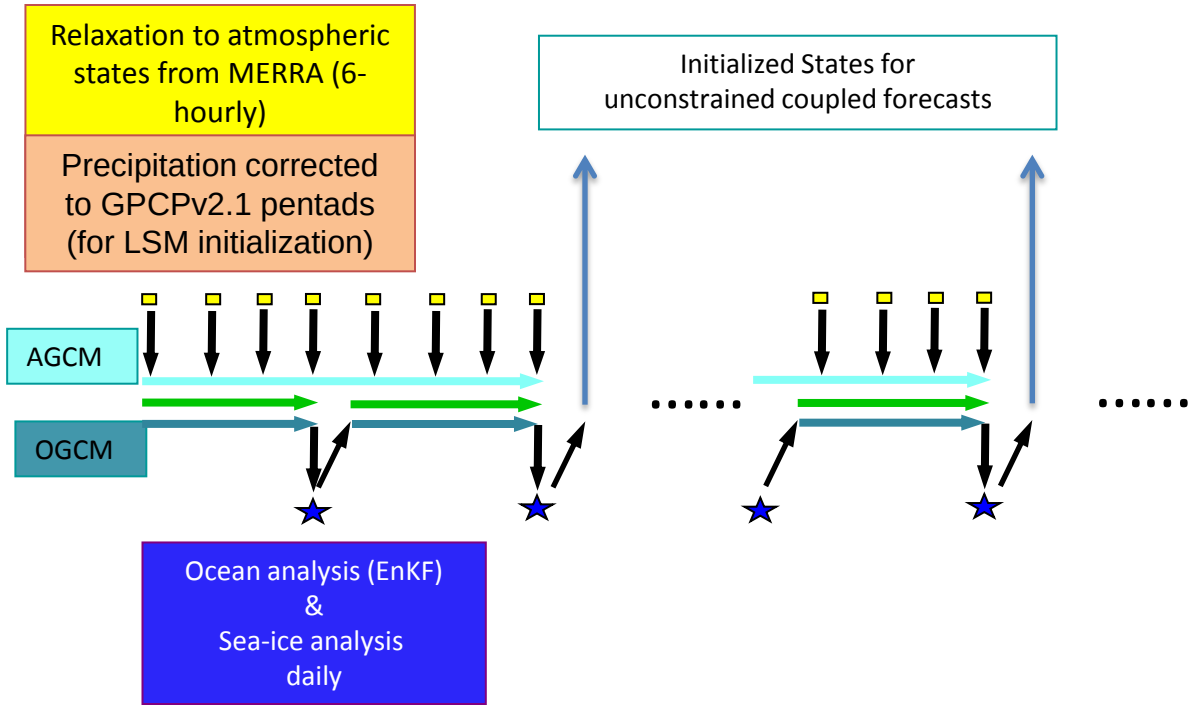
Different moisture levels (shown here as different water table depths)…

…lead to different areal partitionings of the catchment land element into saturated, unstressed, and wilting regimes.

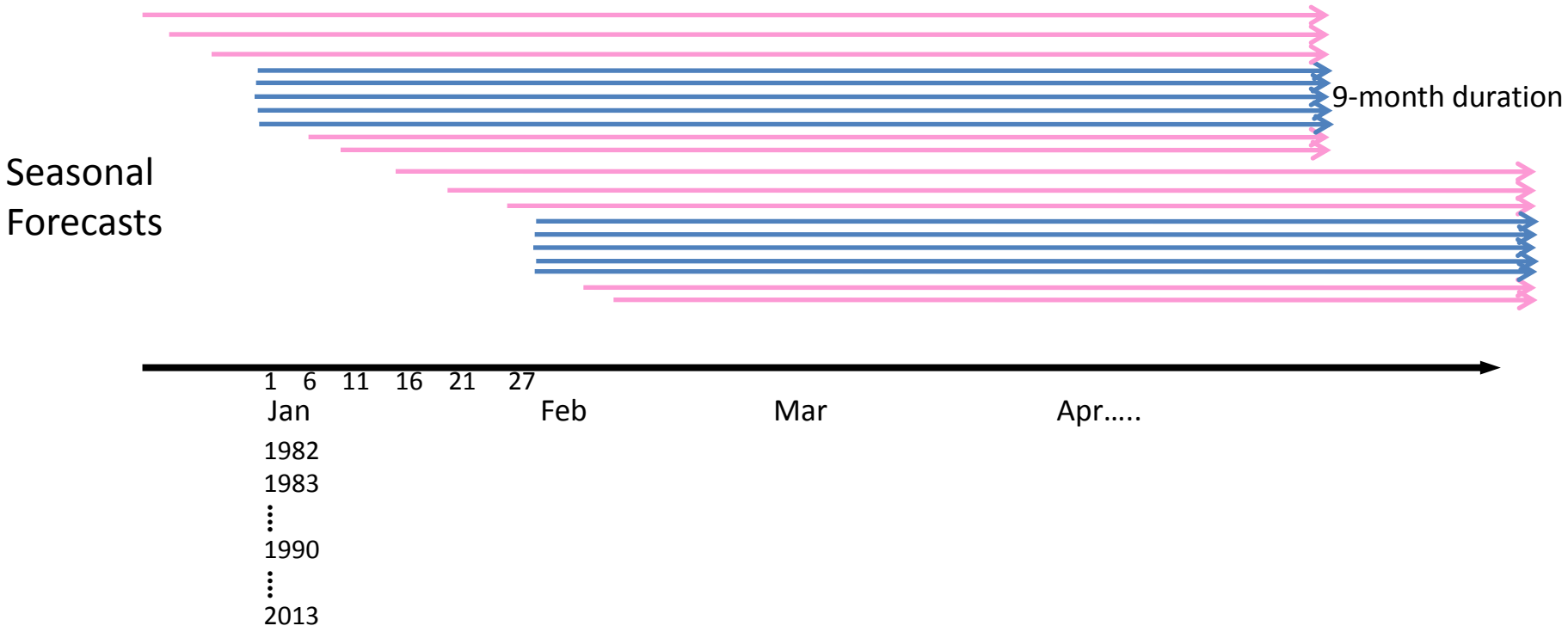
Different, *regime-specific* physics are applied in the different subgrid areas.

GEOS-5 Coupled analysis cycle for Initialization of ISI Predictions

GEOS-5 AOGCM integration



Seasonal Forecast strategy with GEOS-5



Seasonal ensembles:
1st of month: Bred Vector perturbations (1-month rescaling) and/or coupled EnKF perturbations
Later initialization to subsample subseasonal evolution in initial conditions

Forecast anomalies calculated relative to ensemble climatological drift for each start date

The forecast simulations produce, at the resolution of the models, global fields of

- SST
- subsurface ocean temperatures
- atmospheric circulation patterns
- continental precipitation and air temperature
- soil moisture
- etc., etc.

These forecasted quantities have many potential uses…

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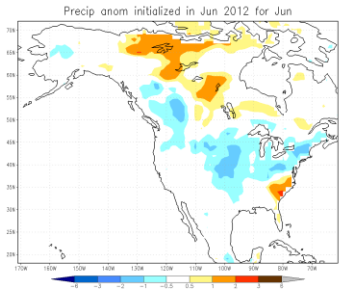
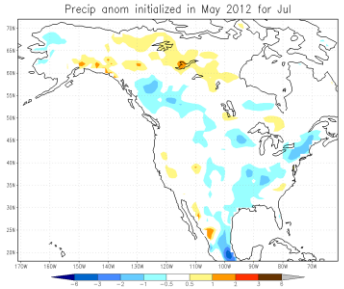
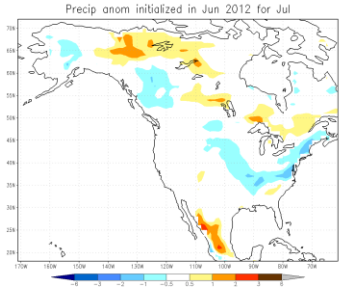
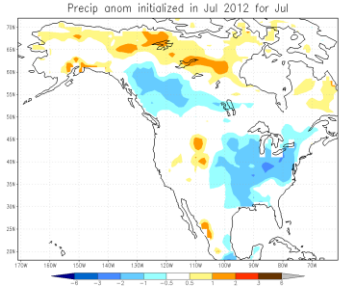
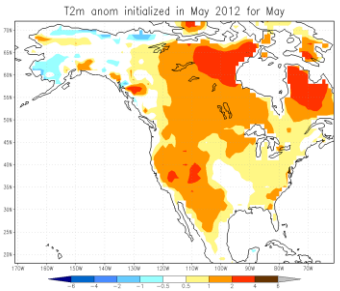
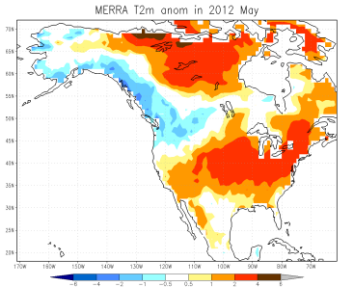
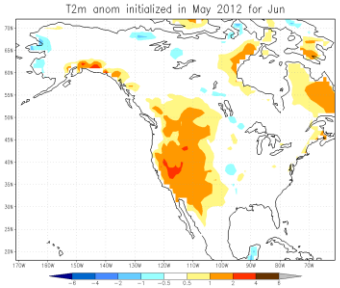
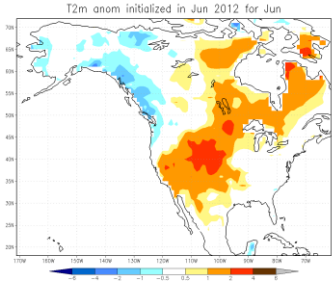
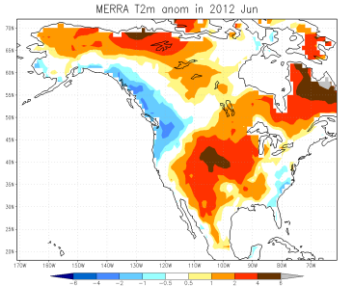
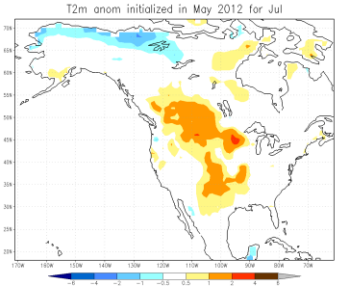
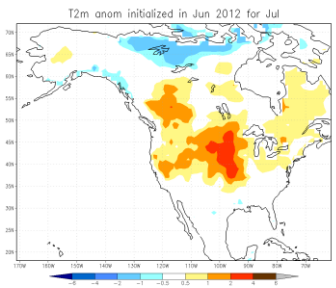
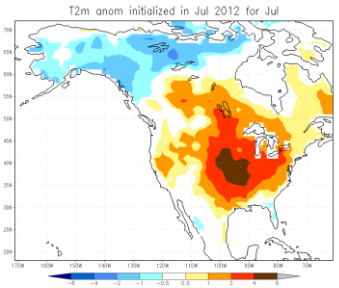
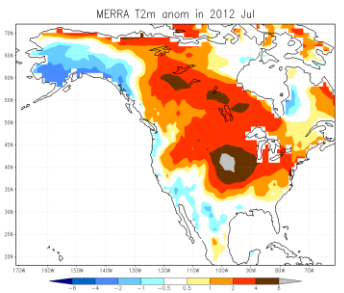
- Expectations for improved soil moisture estimation through new sensors

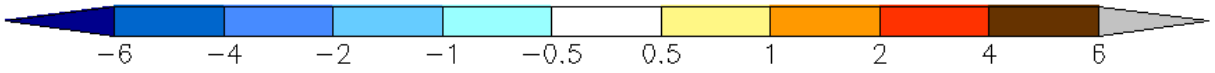
Precipitation Anomaly Forecasts: Summer 2012

	Predicted in early May	Predicted in early June	Predicted in early July	Observations (MERRA)
May				
June				
July				

−6 −3 −2 −1 −0.5 0.5 1 2 3 6

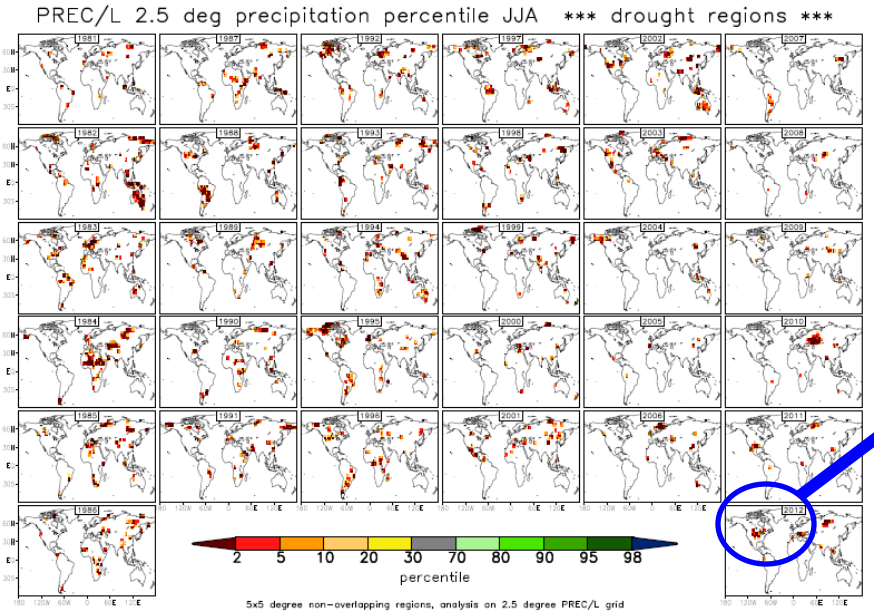
Temperature Anomaly Forecasts: Summer 2012

	Predicted in early May	Predicted in early June	Predicted in early July	Observations (MERRA)
May				
June				
July				



Global evaluation of drought forecasts over the period 1981-2012 with the GMAO forecast system

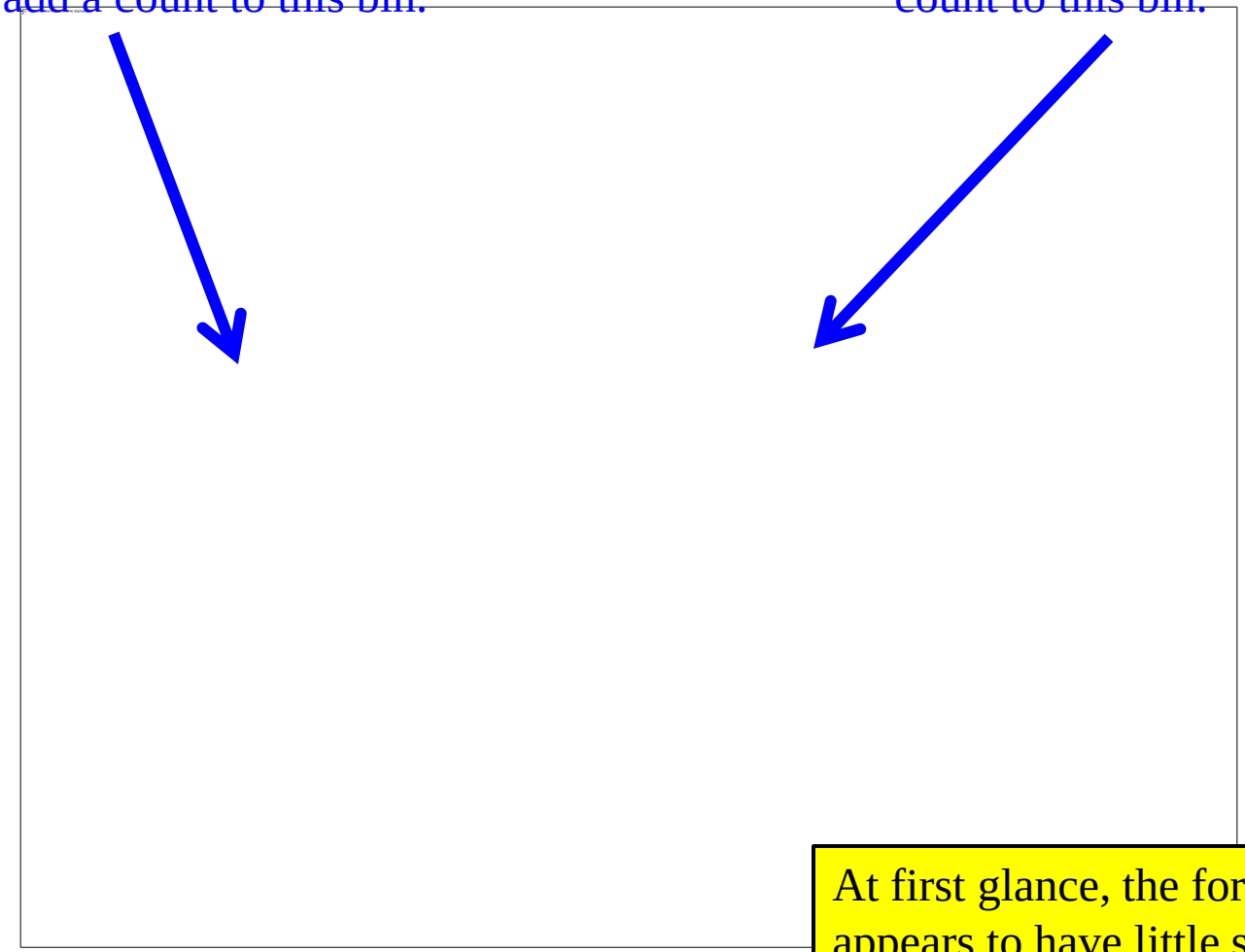
Step 1: For each 5ºx5º area, determine times for which the observations show JJA precipitation to be in the lowest (driest) decile.



Step 2: Determine whether the corresponding GCM forecasts (initialized in early June) also place the JJA precipitation there in the lowest decile.

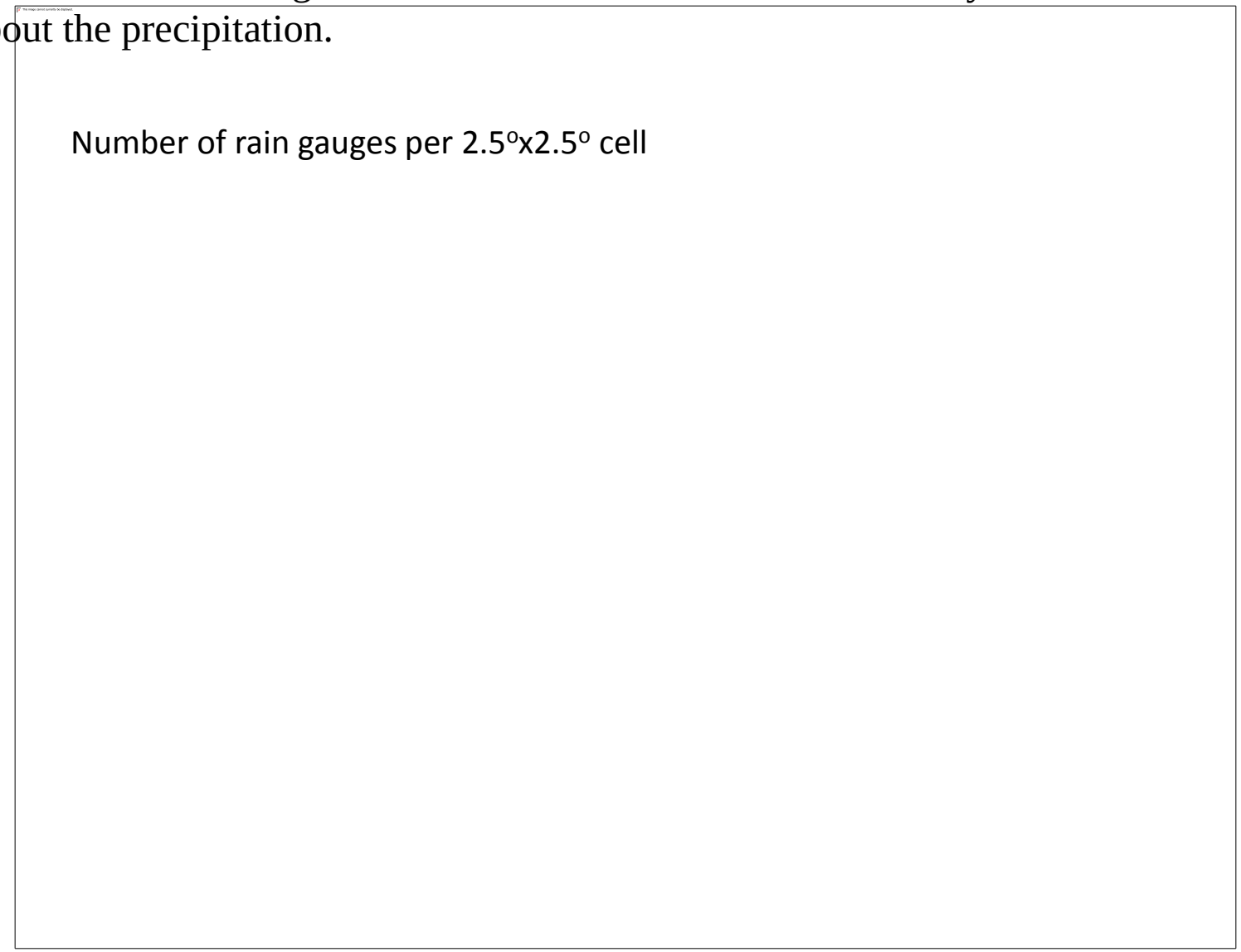
If, in a given instance, the forecast system accurately predicted JJA precipitation to be in the lowest decile, add a count to this bin.

If the forecast system predicted precipitation to be in the 60%-70% decile, add a count to this bin.



At first glance, the forecast system appears to have little skill.

Note, however, that in the binning procedure, we are giving equal weight to all predictions, including those in locations for which we have very little information about the precipitation.



We can weight the counts added to a given bin by the density of rain gauges within the area considered ➡ perhaps a fairer approach to evaluating forecast skill.

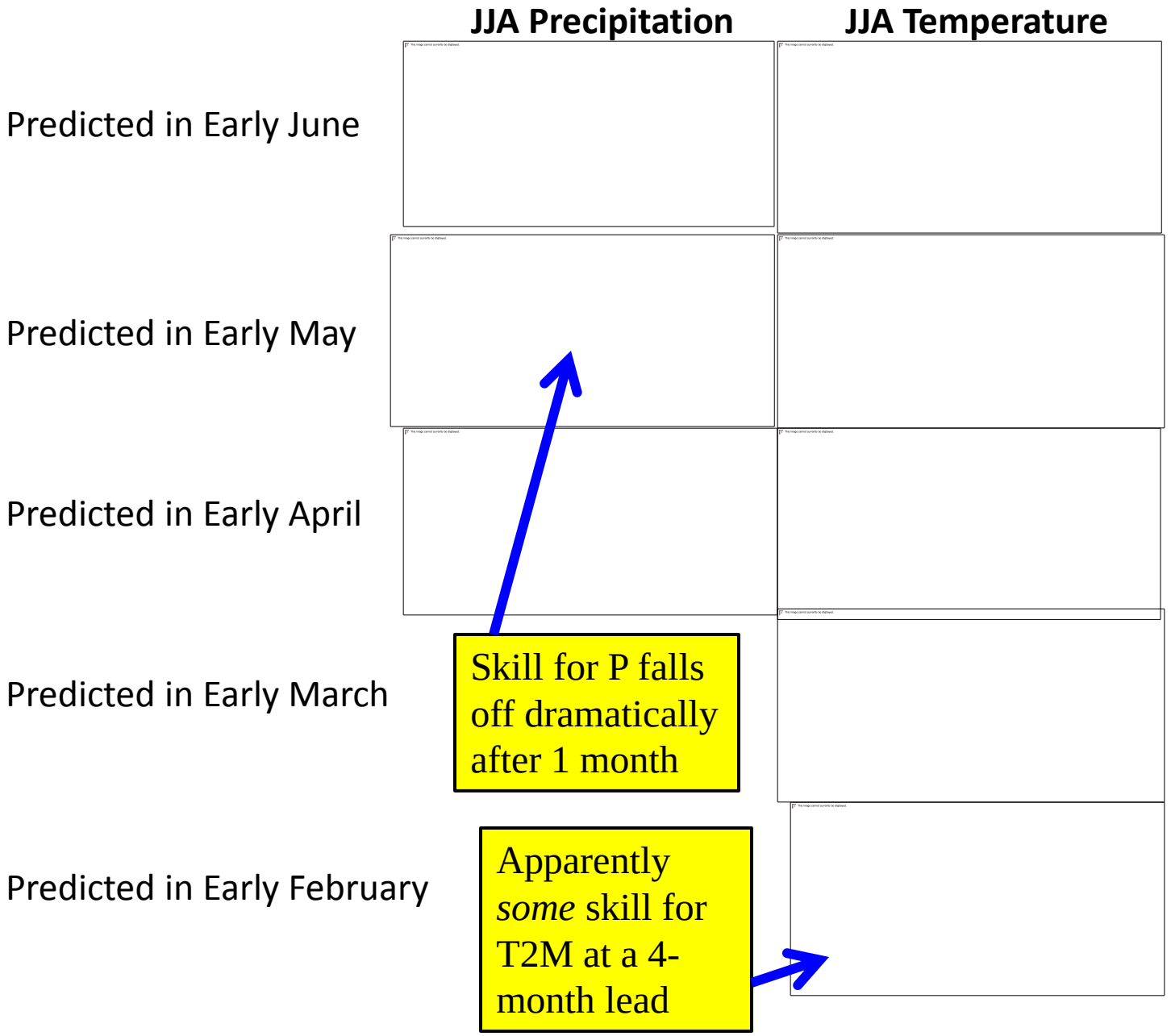
Now perform a similar exercise for air temperature (T2M):

1) Determine the instances for which the observations show JJA temperatures (at 5^{o}x5^{o}) to be in the warmest decile.
2) Bin the forecasted JJA T2M percentiles for these instances accordingly.

Skill in predicting hot summers seems quite good!

(Note: precipitation gauge density weighting is used here also in order to address the soil moisture initialization mechanism.)

Skill as a function of lead



Topics covered:

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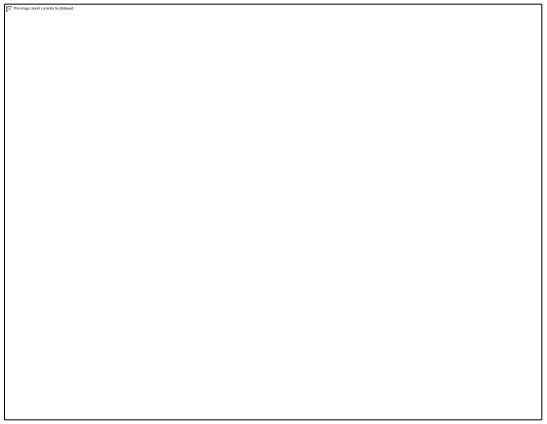
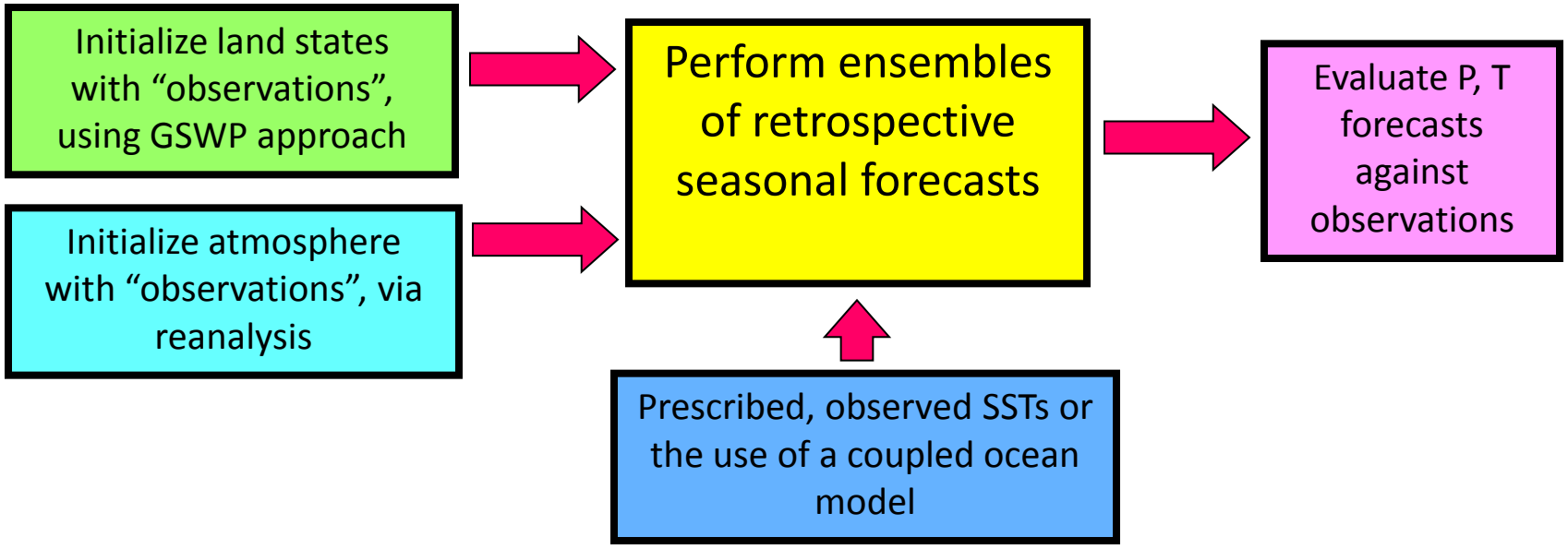
GLACE-2: An international project aimed at quantifying soil moisture impacts on prediction skill.

Overall goal of GLACE-2: Determine the degree to which realistic land surface (soil moisture) initialization contributes to forecast skill (rainfall, temperature) at 1-2 month leads, using a wide array of state-of-the-art forecast systems.



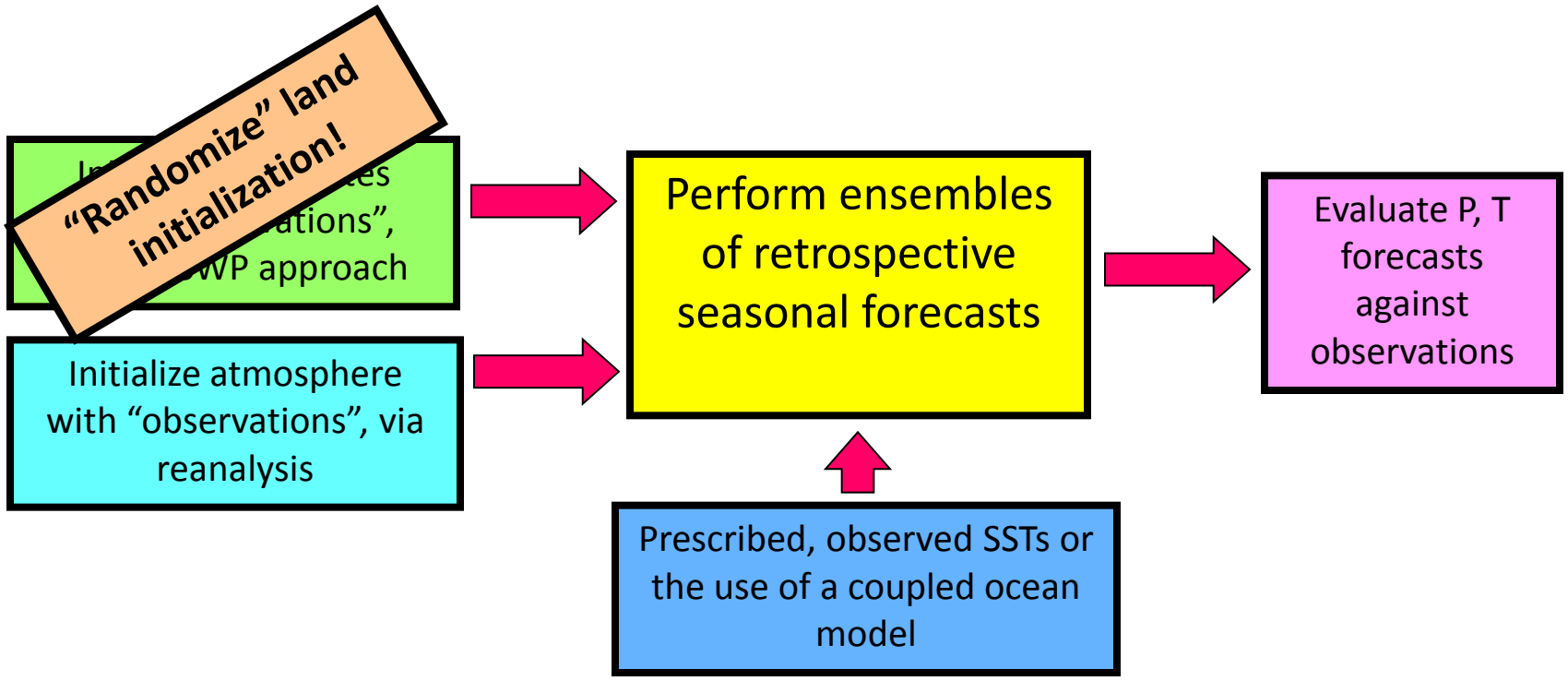
GLACE-2:
Experiment Overview

Series 1:



GLACE-2:
Experiment Overview

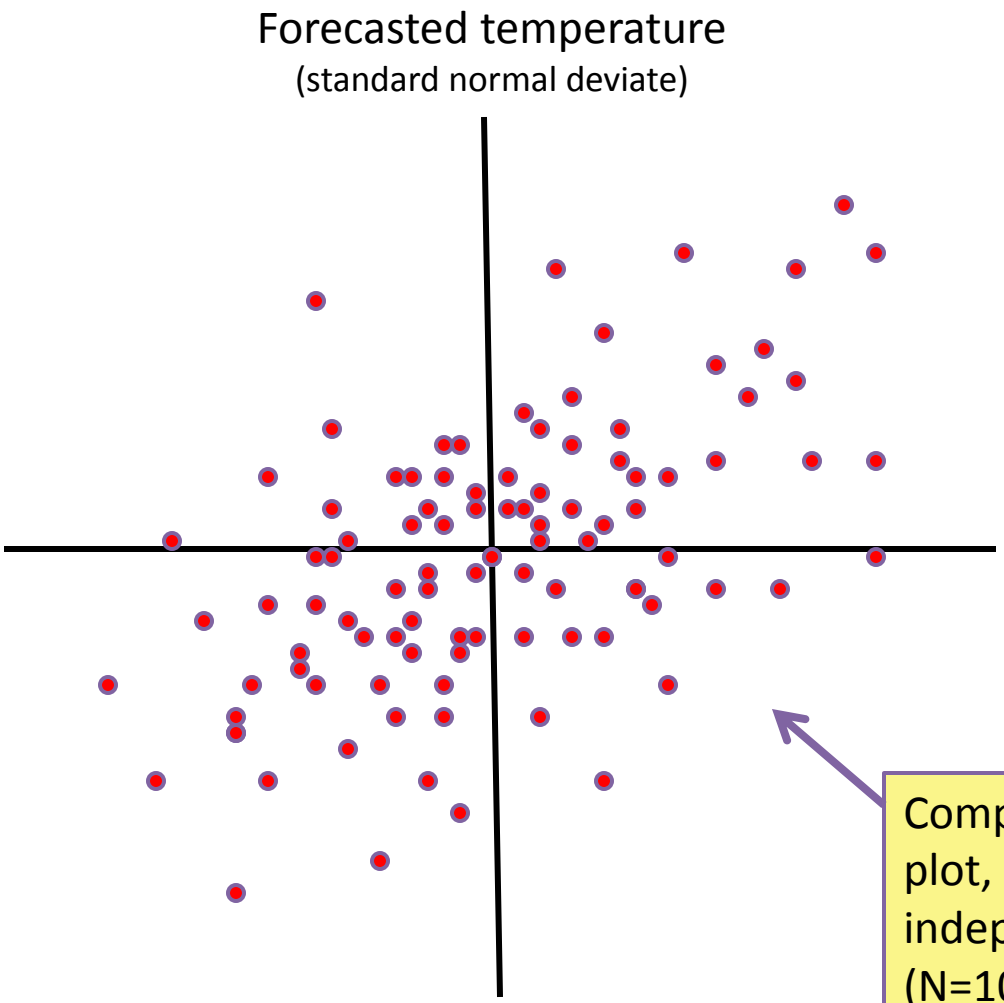
Series 2:



GLACE-2:
Experiment Overview

Step 3: Compare skill in two sets of forecasts; isolate contribution of realistic land initialization.

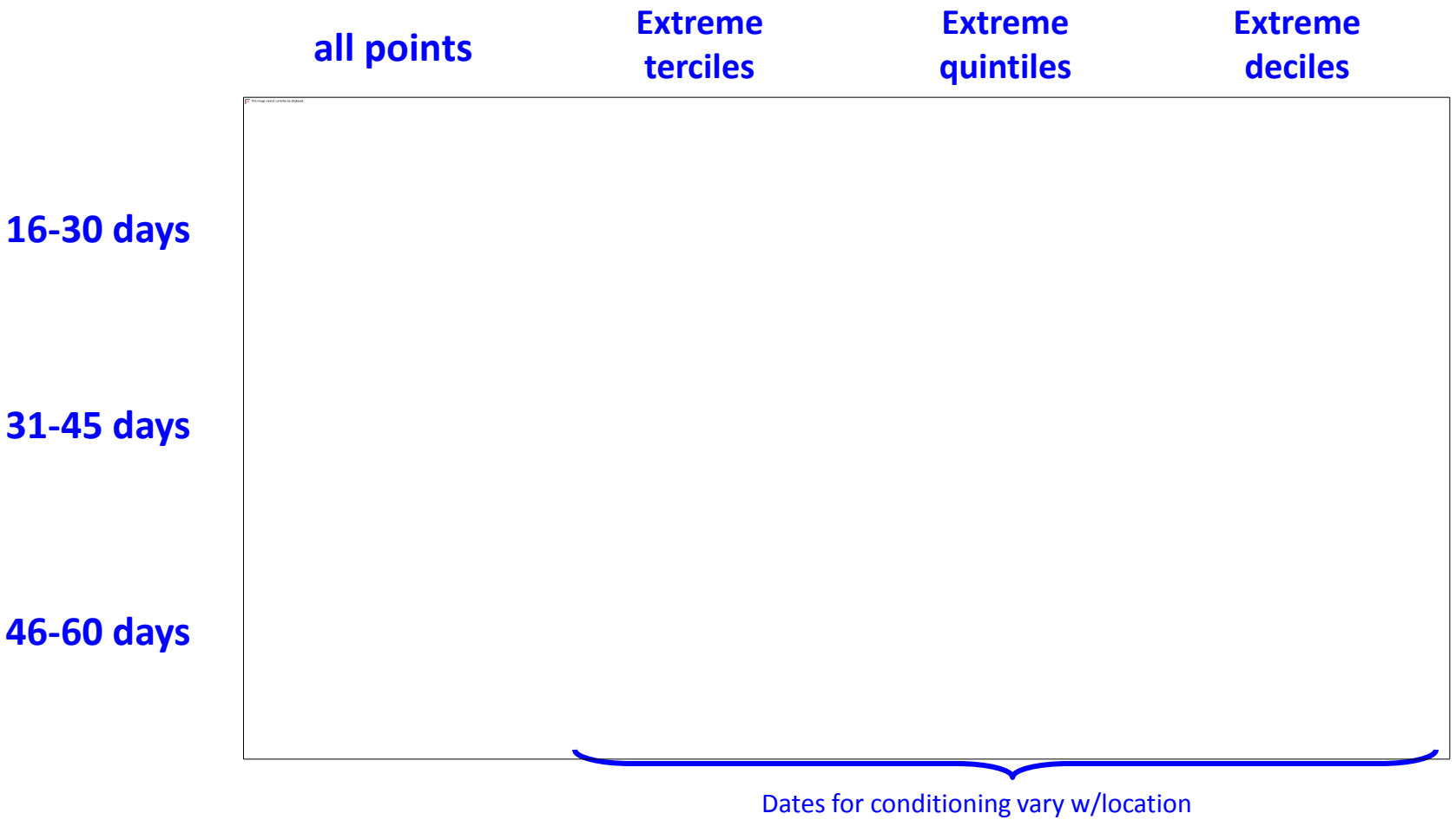
Skill measure: r^2 when regressed against observations



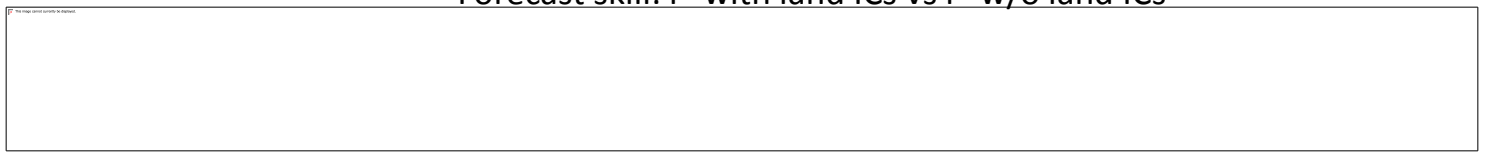
Observed temperature
(standard normal deviate)

Compute r^2 from N points in scatter plot, one point for each of the N independent forecasts.
(N=100 for MJJAS; N=60 for JJA)

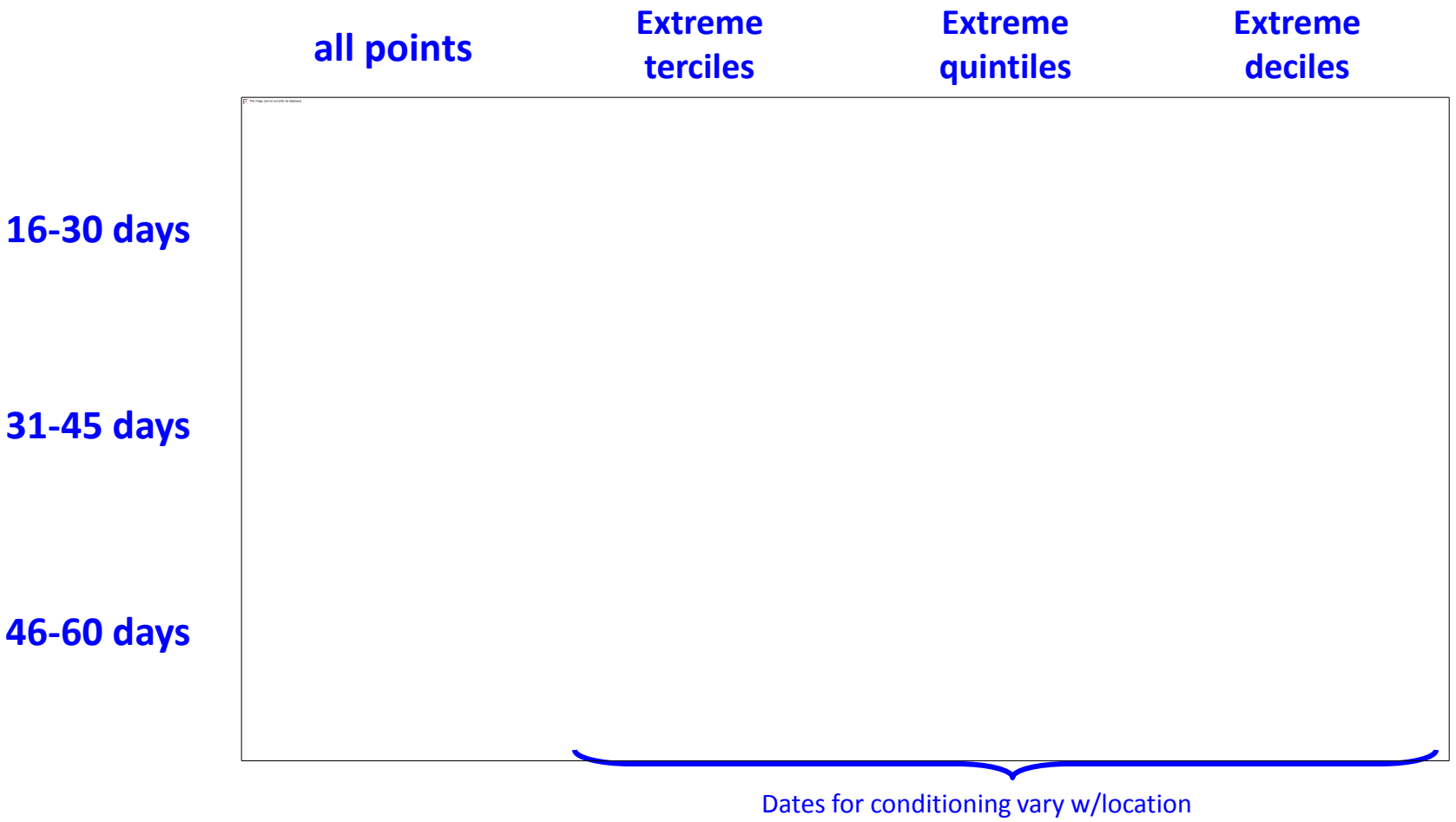
Temperature forecasts: Increase in skill due to land initialization (JJA)
(conditioned on strength of local initial soil moisture anomaly)



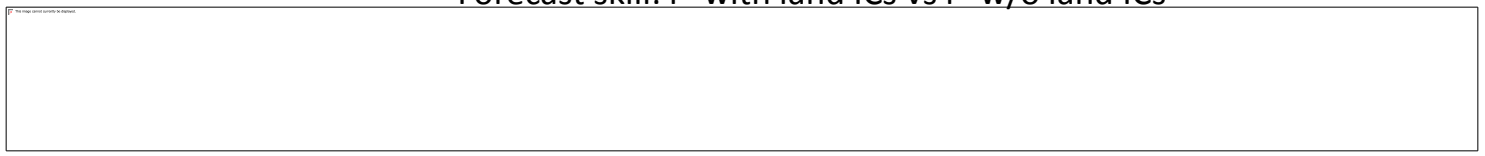
Forecast skill: r^2 with land ICs vs r^2 w/o land ICs



Precipitation forecasts: Increase in skill due to land initialization (JJA)
(conditioned on strength of local initial soil moisture anomaly)

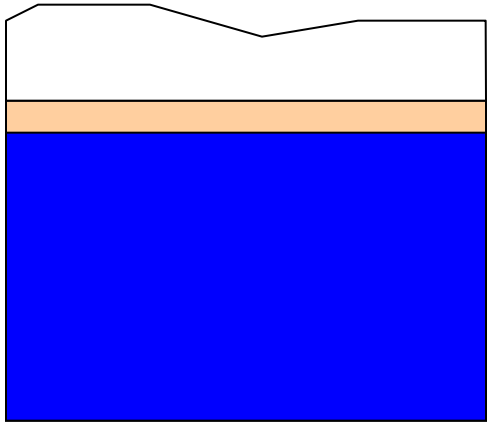


Forecast skill: r^2 with land ICs vs r^2 w/o land ICs



Streamflow Prediction

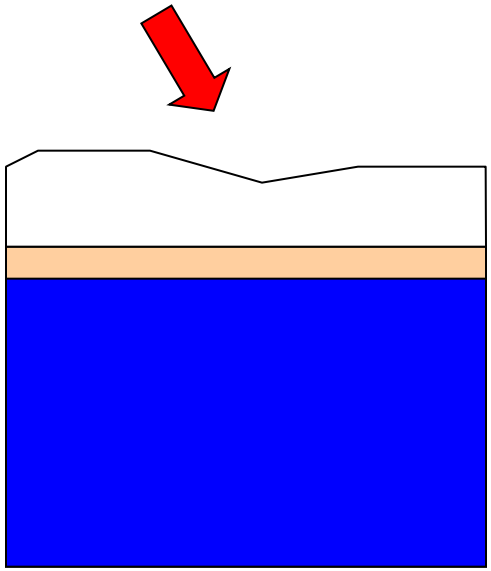
Obvious: Larger snowpack ⇨ Increased streamflow during snowmelt season.



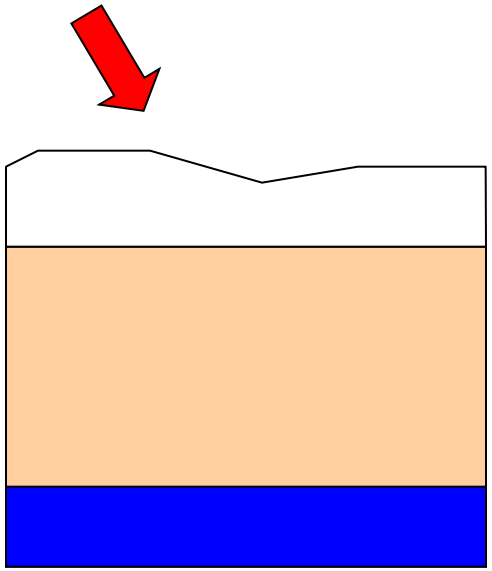
Knowledge of winter snow ⇨ streamflow forecast skill

Less obvious: Impact of soil moisture

Snow (or rainfall) over wet soil: most of the meltwater runs off into streams, reservoirs



Snow (or rainfall) over dry soil: most of the meltwater infiltrates the soil and is lost to water resources



Knowledge of winter soil moisture ⇨ streamflow forecast skill

Quantify with experiment:

1. Perform multi-decadal offline simulation covering CONUS, using observations-based meteorological data. Determine streamflows in various basins for different seasons and compare against (naturalized) streamflow observations.

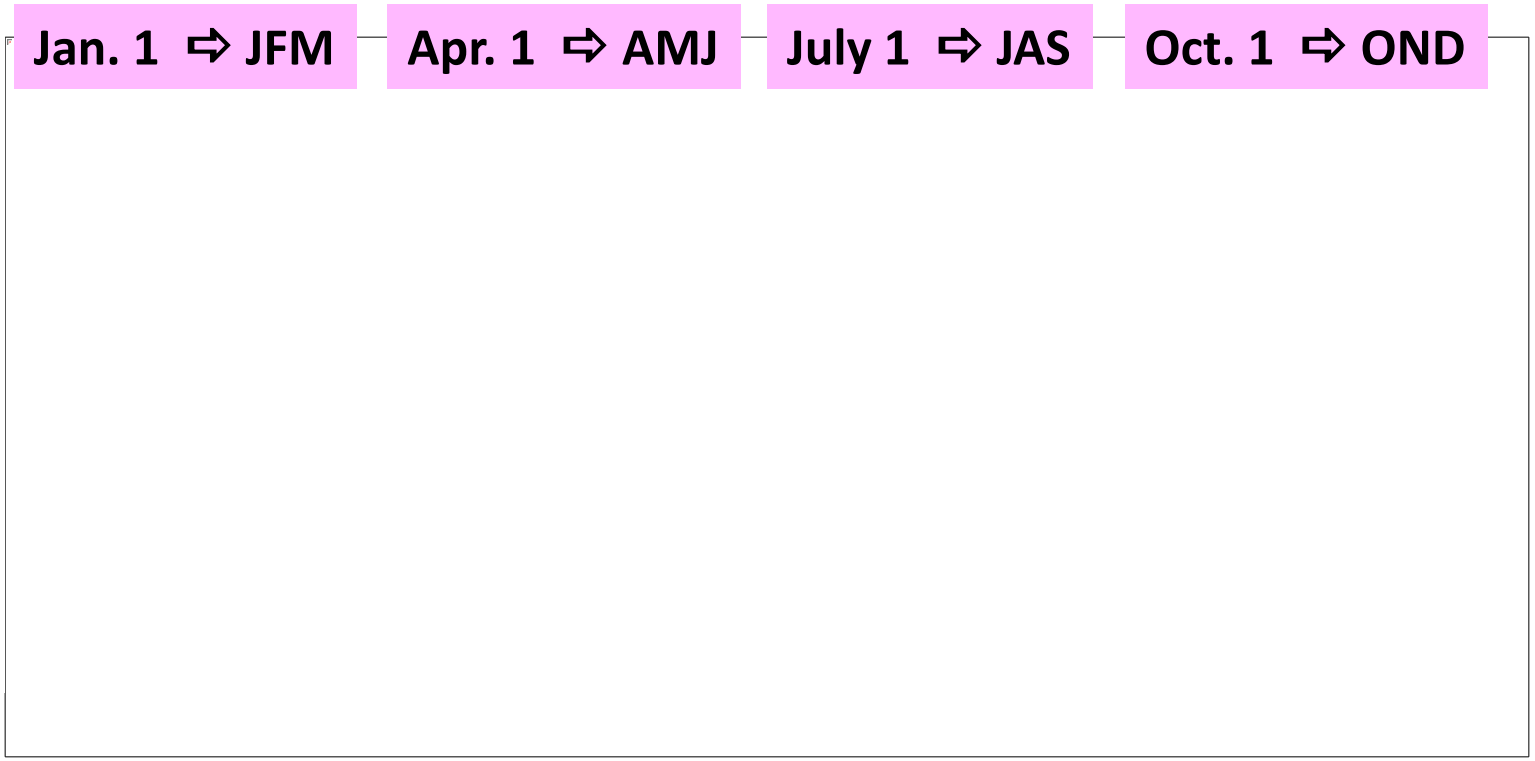
2. Repeat, but doing forecasts: Simulate seasonal streamflow knowing only soil moisture and snow conditions at the start of the season. (Use climatological met forcing during forecasts.) Compare forecasts to observations. ***(Not a synthetic study!)***

3. Repeat, knowing only snow conditions on Day 1.

4. Repeat, knowing only soil moisture conditions on Day 1.

Skill as a function of start date:

Results for 3-month forecasts at zero lead



⇨ ***Outside of spring, soil moisture's contribution to skill outweighs that of snow.***

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- How well does it do? (A focus on drought and hot summers)
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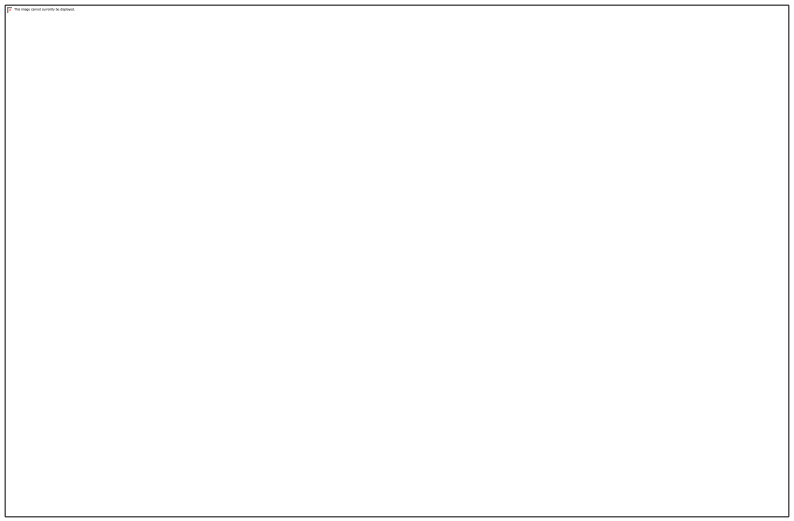
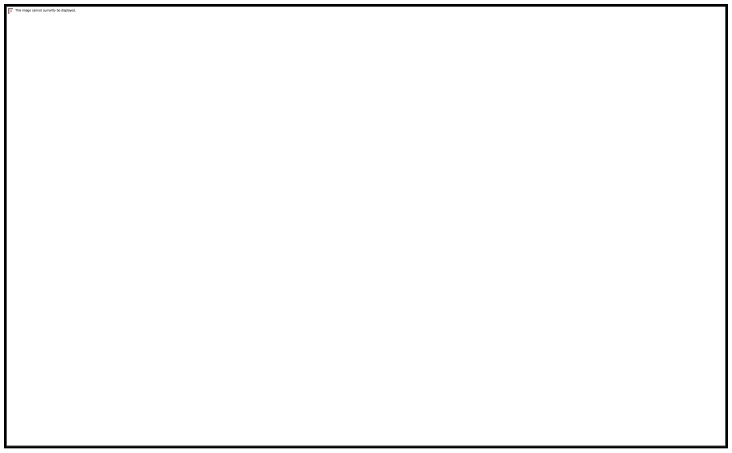
Soil Moisture Monitoring





% vol. soil moisture

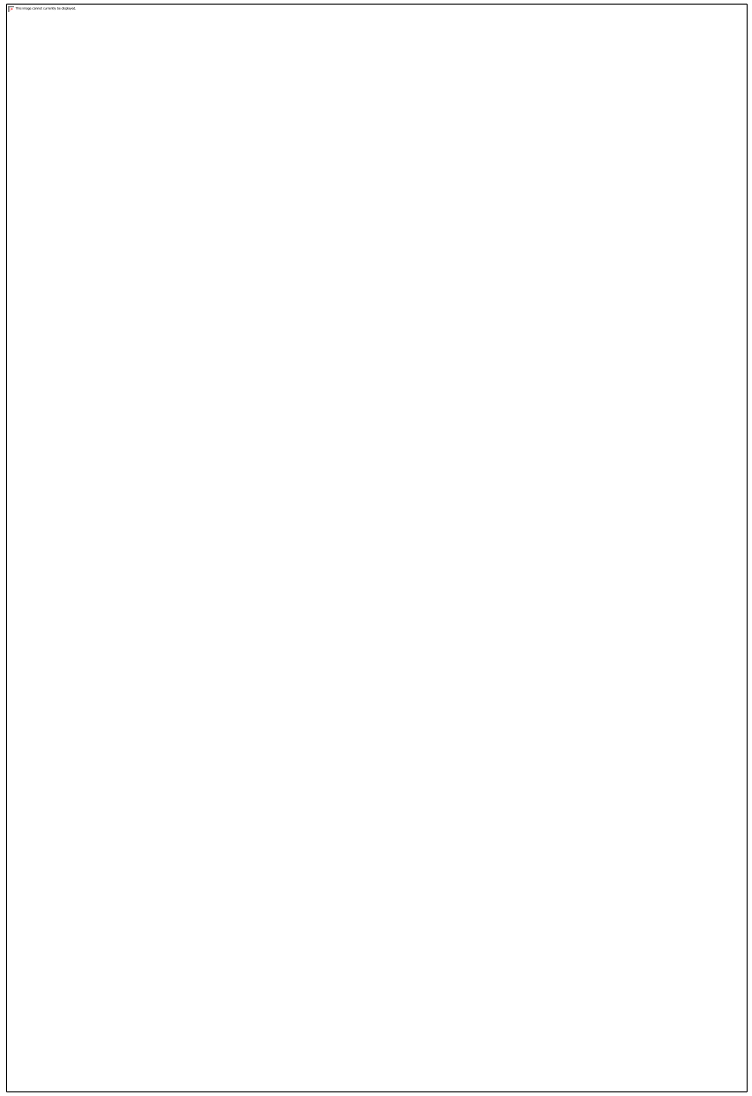
Limitations of current approaches

- Installed in situ network has inadequate coverage, particularly at global scale
- Existing space-borne sensors have inadequate sensitivity & resolution

For soil moisture, SMAP provides:

- High revisit time (2-3 days)
- High spatial resolution (10 km)
- Depth to 5 cm (Level 2)
- Depth through the root zone (Level 4, with data assimilation)

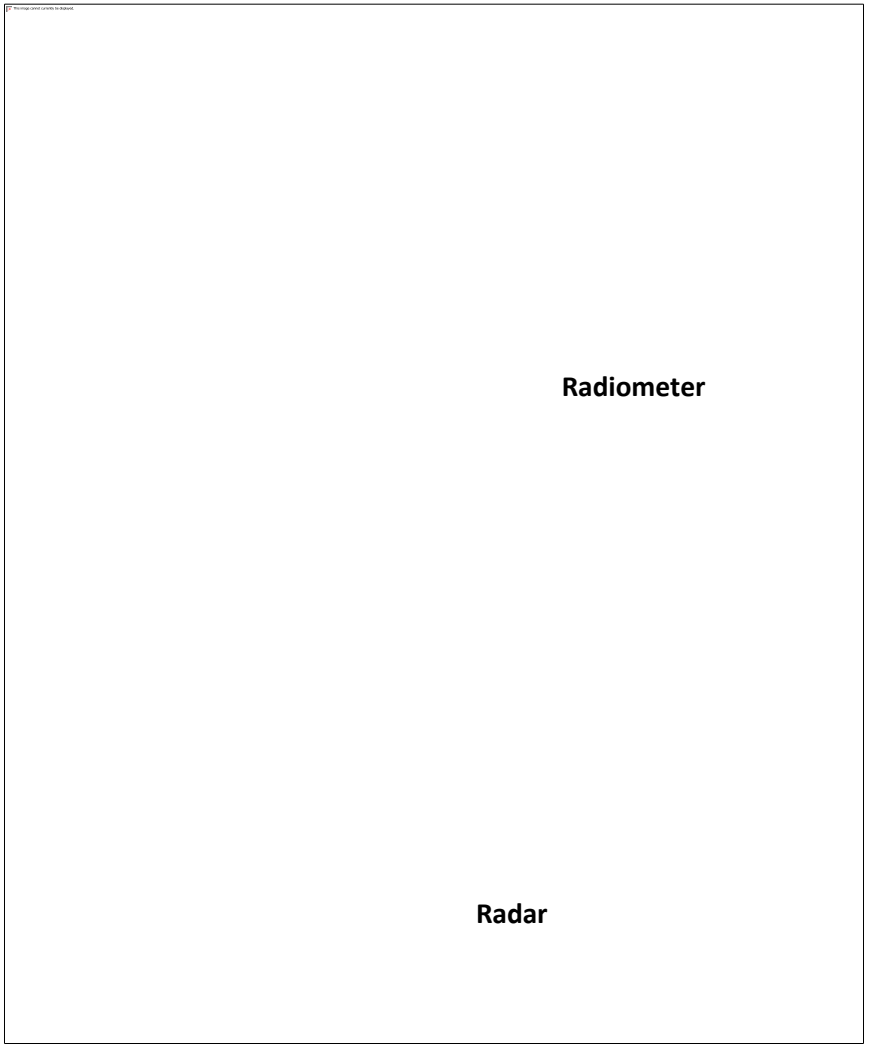
SMAP Mission Concept



- L-band unfocused SAR and radiometer system with offset-fed 6-m light-weight deployable mesh reflector rotating about nadir axis (14.6 rpm)
  - Single feed (dual-pol radar and polarimetric radiometer)
  - Conical scan, fixed incidence angle across swath
  - Contiguous 1000 km swath
  - Radar resolution: 1-3 km (degrades over center 30%)
  - Radiometer resolution: 40 km
- Sun-synchronous dawn/dusk orbit
- Mission Ops duration 3 years

L-band Active/Passive Measurement Concept and Heritage

- Soil moisture retrieval algorithms are derived from a long heritage of microwave modeling and field experiments
  - MacHydro'90, Monsoon'91, Washita'92, FIFE, HAPEX, SGP'97,'99, SMEX'02–'05, SMAPVEX'08
- **Radiometer—**High accuracy (less influenced by roughness and vegetation) but coarser spatial resolution (40 km)
- **Radar—**High spatial resolution (1–3 km) but more sensitive to surface roughness and vegetation
- **Combined Radar-Radiometer** product provides optimal blend of resolution and accuracy to meet science objective



SMAP Baseline Science Data Products

Data Product Short Name	Short Description	Spatial Resolution	Latency*
L1A_S0	Radar raw data in time order		?
L1A_TB	Radiometer raw data in time order		?
L1B_S0_LoRes	Low resolution radar σ_o in time order	5x30 km (10 slices)	12 hours
L1B_TB	Radiometer T_B in time order	36 km	12 hours
L1C_S0_HiRes	High resolution radar σ_o on swath grid	1-10 km	12 hours
L1C_TB	Radiometer T_B on earth grid	36 km	12 hours
L2_SM_A	Soil moisture (radar)	3-10 km	24 hours
L2_SM_P	Soil moisture (radiometer)	36 km	24 hours
L2_SM_A/P	Soil moisture (radar/radiometer)	9 km	24 hours
L3_F/T_A	Freeze/thaw state (radar, daily composite)	3 km	30 hours
L3_SM_A	Soil moisture (radar, daily composite)	3 km	30 hours
L3_SM_P	Soil moisture (radiometer, daily composite)	36 km	30 hours
L3_SM_A/P	Soil moisture (radar/radiometer, daily composite)	9 km	30 hours
L4_SM	Soil moisture (surface & root zone)	9 km	7 days
L4_C	Carbon net ecosystem exchange (NEE)	9 km	14 days

Global Mapping L-Band Radar and Radiometer

High-Resolution and Frequent-Revisit Science Data

Obs.+Model Value-Added Product

* To be Confirmed

Overall Summary

Topics covered:

- Overall design of the GMAO seasonal forecast system

  State-of-the-art system; 9-month forecasts in real time.

- How well does it do? (A focus on drought and hot summers)

  Hot summer predictions somewhat skillful; dry summers less so.

- GMAO studies of how soil moisture information contributes to prediction skill

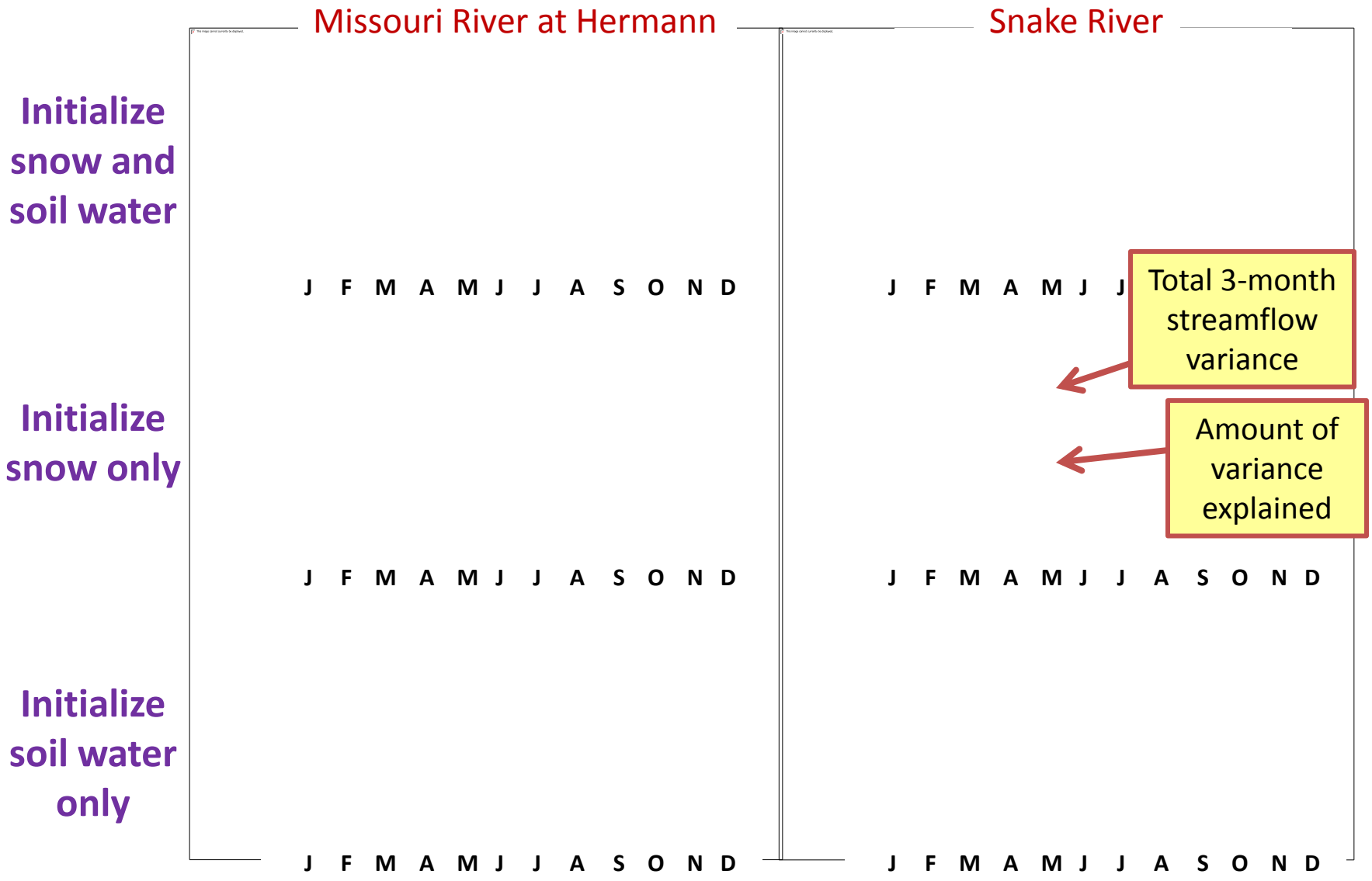
Soil moisture initialization provides significant skill, especially for runoff and for temperature forecasts under extreme ICs.

- Expectations for improved soil moisture estimation through new sensors

The upcoming NASA SMAP soil moisture sensor, along with the European SMOS instrument, should provide valuable soil moisture information that can translate into prediction skill.

(Extra slides)

Preliminary κ calculation from a single global run


Missouri River at Hermann
Snake River
Initialize snow and soil water
Initialize snow only
Initialize soil water only
J F M A M J J A S O N D
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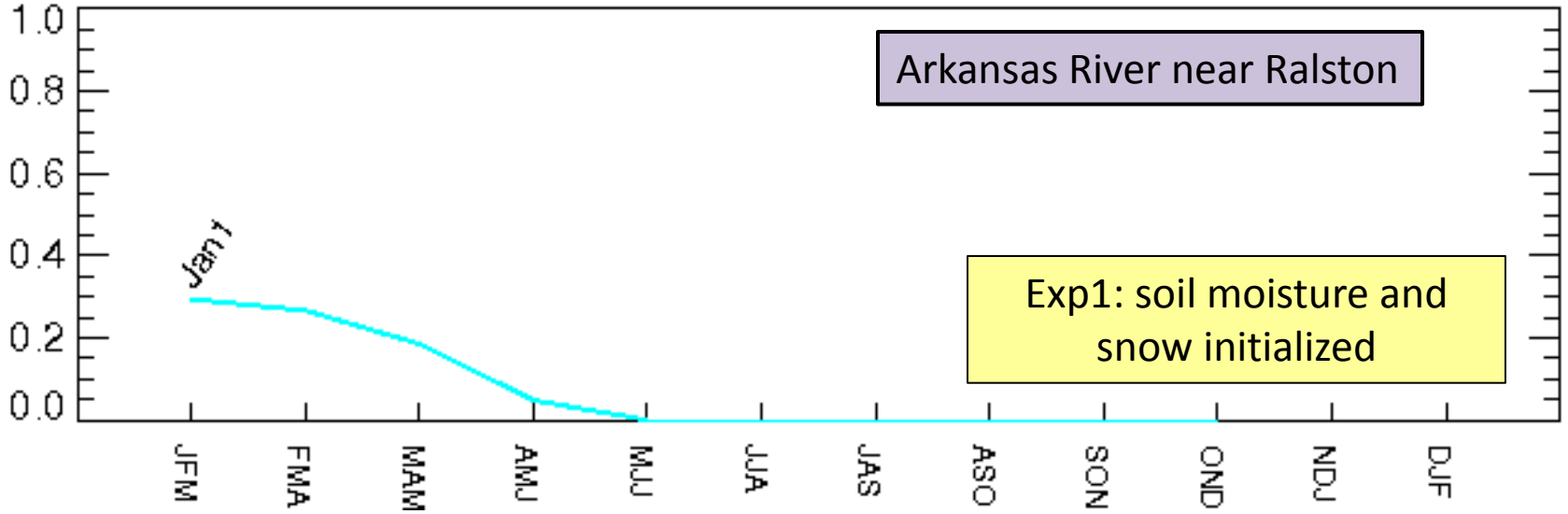
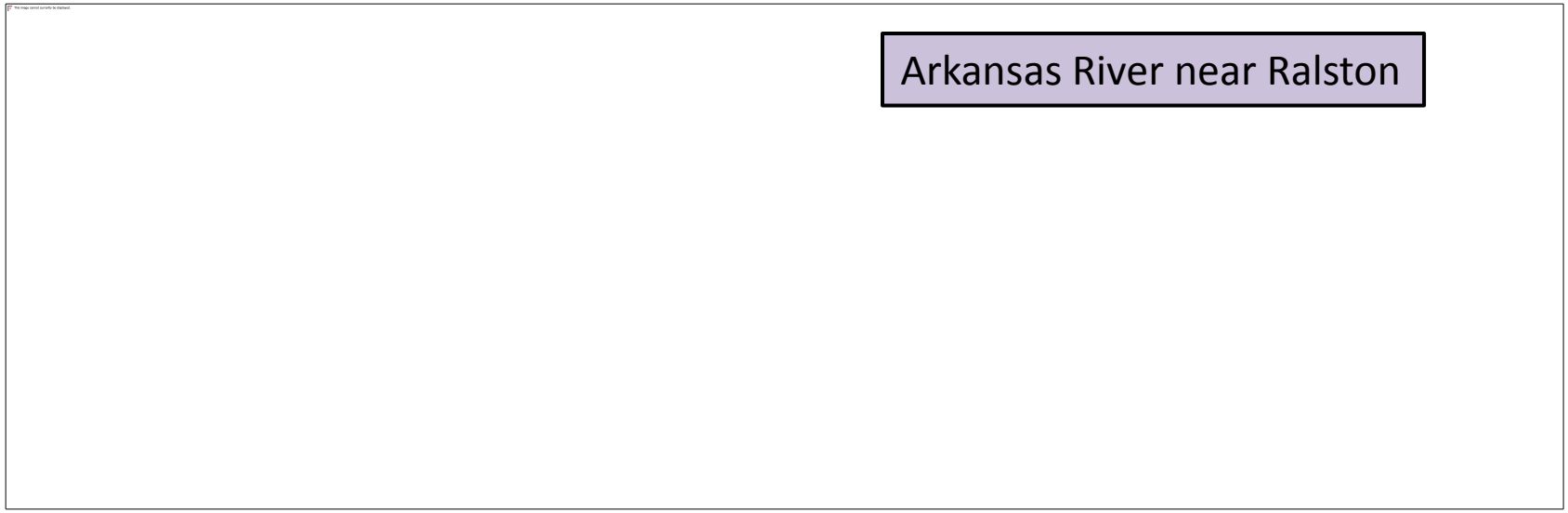
Total 3-month streamflow variance
Amount of variance explained

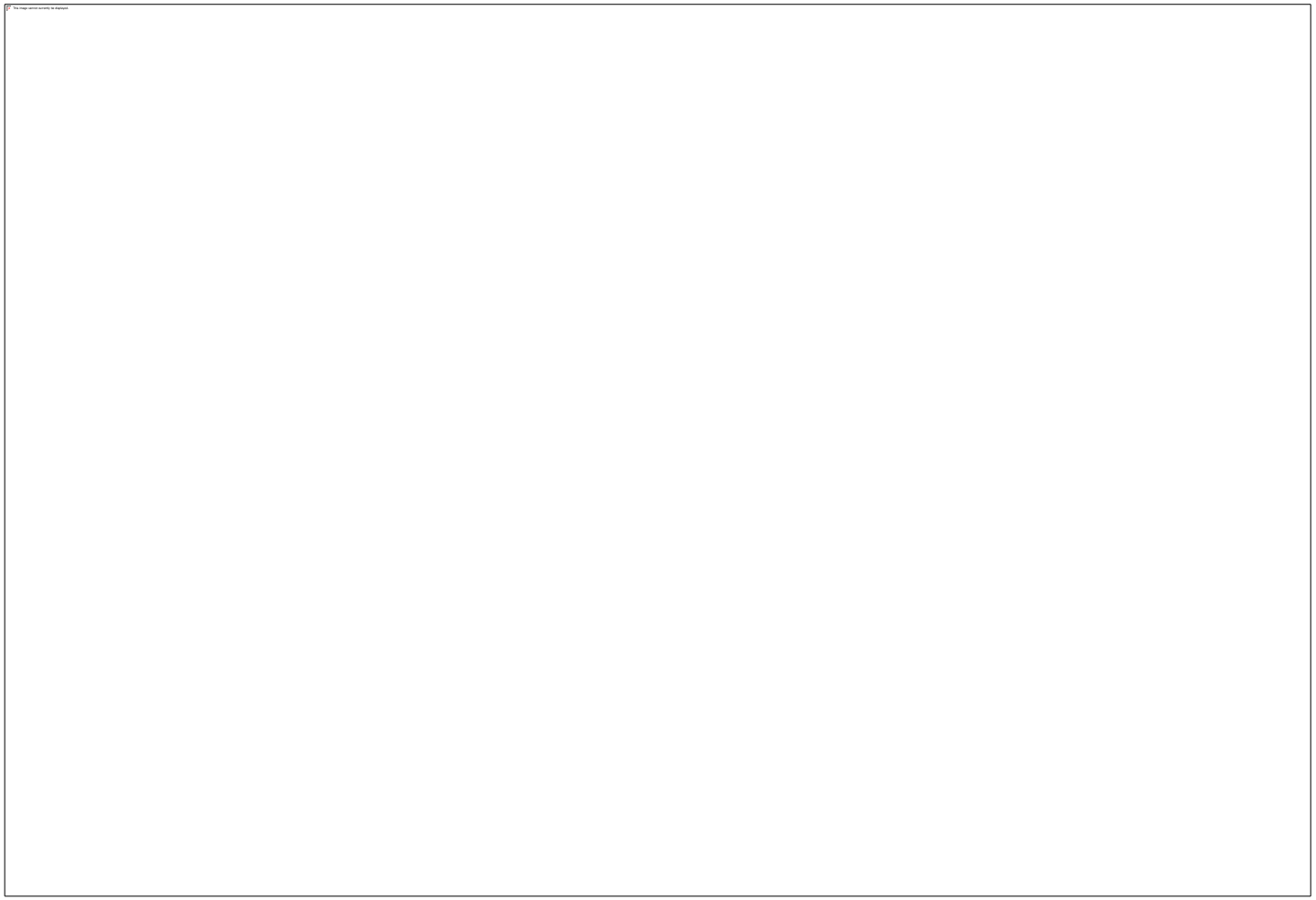
Forecast skill (for 3-month totals) as a function of lead



Forecast skill (for 3-month totals) as a function of lead and start date



$\frac{\sigma_{runoff}}{\mu_{runoff}}$



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The current GMAO Seasonal Forecast System

GEOS-5 AOGCM

Atmosphere: Initialized from MERRA

AGCM: GEOS-5 AGCM, 1 x 1.25 x L72

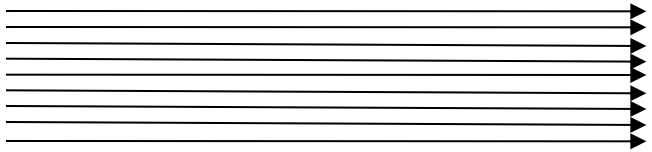
Land: taken from MERRA_Land

LSM: Catchment

Ocean: Initialized from GEOS-iODAS

OGCM: MOM4, 1/2 x 1/2 x L40, with ¼ equatorial refinement

9 month Coupled Integrations:
11 ensemble members
Initialized beginning of each month and every 5 days
Forecasts delivered to CTB on the 8th of the month



AOGCM: Full coupling.
No flux correction

ODAS: (Conducted in AOGCM with atmosphere constrained by MERRA
Ocean analysis assimilates in situ temperature and salinity profiles, Reynolds SST, sea level anomalies derived from satellite altimeter)
MERRA: Atmospheric analysis for the satellite era using GEOS-5
MERRA_Land: Catchment LSM forced by MERRA surface fluxes with a correction to precipitation

Coupled A-L-O-S initialization of seasonal predictions

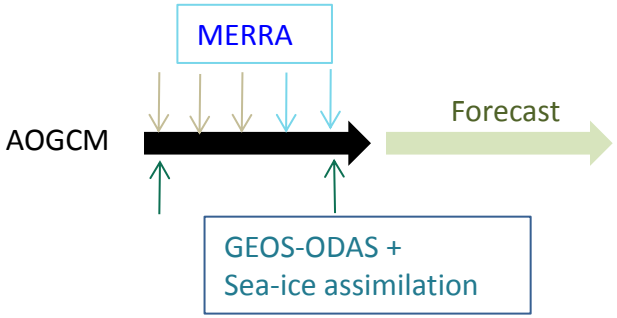
Atmosphere constrained by MERRA every 6 hours

- Precipitation rescaled to GPCP for LSM

Ocean: daily assimilation

- Ensemble Optimal Interpolation (EnOI)
- State dependent localization based on density
- 1960 to present

Sea-ice: daily assimilation of sea-ice concentration

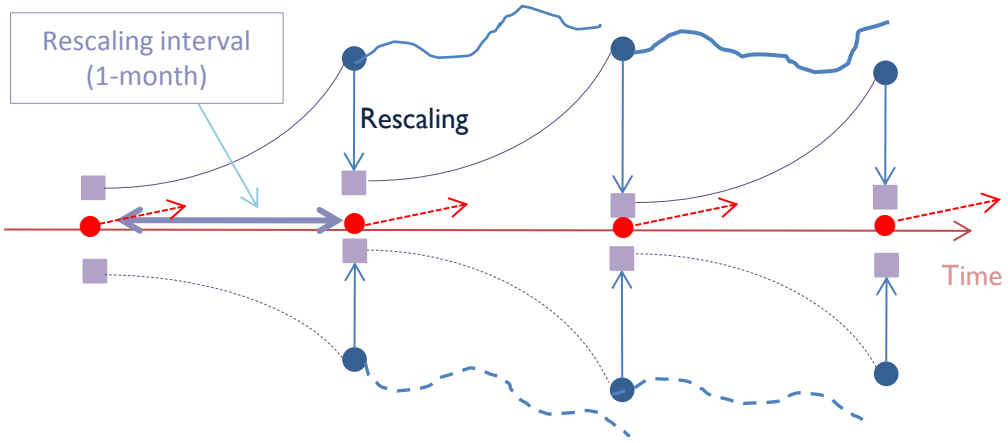


(5% of global profiles, randomly chosen)

(Temperature profiles corrected à la Levitus; synthetic salinity profiles)

Next: Generation of Ensemble Perturbations

- Method : **Two-sided breeding**
- Norm variable : **SST**
- Norm Region : **Equatorial Pacific (5S-5N)**
- Initial BV magnitude : **Reduced to 10% of natural variability**
- Rescaling Interval : **1-month**



1st EOF of HC300 from BVs

- IC: A-L-O-S Reanalyses
- Bred Vectors
- Perturbation from BV